TEXAS TRANSPORTATION INSTITUTE

TEXAS HIGHWAY DEPARTMENT

COOPERATIVE RESEARCH

Deflections in Flexible Pavements
2-8-54-1

in cooperation with the
Department of Commerce
Bureau of Public Roads

BIBLIOGRAPHY 67-4

SURVEY OF LIBRARY FACILITIES PROJECT

<u>DEFLECTIONS IN FLEXIBLE PAVEMENTS</u>

1. Designing Bases for Roads and Streets, F. N. Hveem. Pub. Works v 89 n 1 Jan. 1958 p 97-100.

   Design chart developed to show required thicknesses of pavement deflection differentials are shown to illustrate differences in deflection over comparable soils and loads for cement treated and gravel bases; principles of structural design and design premises.

2. Application of Rational Design of Flexible Pavements, S. A. Kleyn. S. African Instn. Civ. Engrs - Trans v n 11 Nov. 1958, p 387-408.

   In design of flexible paving, elastic deformation or deflection and plastic deformation or settlement must not exceed certain specific limits, and shear stressed induced in pavement must not exceed shear resistance of system; distinction between and method for evaluating both elastic and plastic deformation; methods for estimating both systems.

3. Increased resistance to deformation of clay caused by repeated loading. H. B. Seed, R. L. McNeill, J. de Guenin. ASCE - Proc v 84 (J Soil Mechanics & Foundations Div) n SM 2, May 1958, pt 1, paper 1645, 28p.

   Influence of stress history, in form of series of repeated stress, applications in increasing resistance to deformation of compacted specimens of silty clay is described and possible causes of effect are presented; significance of results in assessing design life of highway pavements.

4. Laboratory model tests pavement stresses, D. H. Danielson, L. M. LaCross, M. Ekse. Pac. Bldr. &Engr. v 62 n 8 Aug. 1956, p 69-70.

   Device to measure pressure distribution with one type of soil and with different pavement thicknesses, to establish proper thickness of pavement to give favorable distribution of pressure within subgrade constructed at University of Washington; disadvantages of full-sized test track, eliminated by designing device capable of applying variable load at variable speed.

5. Some relations between stress and strain in coarse-grained cohesionless materials, W. Kjellman, B. Jacobson. Roy Swedish Geotechnical Inst. Proc. n 9 1955 42 p.

Fine and coarse pebbles and the fine and coarse macadam tested in loose and in dense state; compresscmeter and direct shear apparatus employed; stress conditions in direct shear test analyzed; Poisson's ratio during first load increase was found to be fairly constant; modulus of elasticity and of rigidity, angle of internal friction, and volume strain during shearing were found to vary considerably.

6. Design of Flexible Pavements, T. Belshaw, P. J. Alley, New Zealand Eng. v 8 n 7 July 1953, p 234-48.

Pavements deformation can be caused by deflection, consolidation deformation, or plastic deformation; standards required for subgrade; compaction and moisture control; methods of determining base course thickness; chart using CBR for design of flexible pavement; soil tests and suggested standards for base course and subbase; determining liquid limit of soil. Bibliography.

7. Testing and design of pavements, S. A. Kleyn, S. African Instn. Civ. Eng. Trans v 2 n 1 Jan. 1952 p 18-32, PRA (Public Roads Administration) classification based on mechanical analysis; liquid limit, plastic limit, plasticity index, shrinkage limit, volumetric change, field mositure, equivalent and centriguge moisture, equivalent and centriguge moisture equivalent; road design curves for flexible pavements based on California bearing ratio; classification of fine grained soils; soils for airport construction.

8. Road deflection under load measured by portable device. Eng. News-Rec. v 151 n 14 Oct. 1 1953 p 29.

Benkelman beam, measures deflection of highway pavement caused by one wheel of loaded truck or trailer as vehicle moves forward at creep speed; due to principle of operation, device is also called lever-arm deflection indicator, description of operation.

9. Dynamic testing of road constructions, C. van der Poel. J. Applied Chem. v 1 pt 7 July 1951 p 281-90.

Deformation of various roads under alternating load; amplitude of loading force ranged from 300-2000 kg force and frequencies from 5-60 cps; results give good impression of mechanical rigidity propogation of vibration, measured at various frequencies, from which dynamic Young' moduli of various construction layers can be calculated; illustrations, diagrams.

10. Pavement Bearing Capacity Computated by Theory of Layered Systems, G. Wilson and G.M.J. Williams. ASCE - Proc. V 76. separate n 16 May 1950. 17 p.

Method for calculating bearing capacity of rigid and flexible pavements; graphs are presented from which required pavement thickness can be obtained directly if loading and physical properties of pavement and subgrade materials are known; commonly used methods for computing bearing capacity; comparison of results.

11. Casagrande, A. and W. L. Shannon: Stress Deformation and Strength Characteristics of Soils Under Dynamic Loads, Proc. 2nd Intern. Conf. Soil Mech. Foundation Eng. v 5 pp 29-34, 1948.

This paper describes apparatus developed and results of tests performed to investigate the stress deformation and strength characteristics of soils under dynamic loads (impulses loading). This is in connection with studies of stability of slopes under the effects of bombing.

12. Poel, C.V.D.: Dynamic Testing of Pavements and Base Coarses, Proc. 2nd Intern. Conf. Soil Mech. Foundation Eng. v 4 pp.157-163. 1948.

Vibration measurements were carried out in different types of runway constructions all laid on the same subsoil. The frequencies used ranged from 10 up to 40 cycles per second. As far as felxible pavements are concerned two rates of propagation of transversal waves were measured: at lower frequencies than in the subsoil, and at higher frequencies than in the foundation. These rates of propagation being directly connected to the modulus of elasticity in shear, they are direct measures of the rigidity of the respective media. In case of a concrete slab lying on the subsoil we measure, besides the rates of wave propagation mentioned above, the flexural vibrations of the slab. From these data the modulus of elasticity of the concrete can be calculated. A theoretical explanation of the influences of the subsoil on the bending waves is given.

13. McLeod, N. W.: Relationships Between Deflections, Settlement, and Elastic Deformation for Subgrades and Flexible Pavements Provided by Plate Bearing Tests at Canadian Airports, Proc. 4th Intern. Conf. Soil Mech. and Foundation Eng. London v 2 pp 151-157, 1957.

For its investigation of airport runway design and evaluation, the Canadian Dept. of Transport employs platebearing test procedure that enables deflection, settlement and elastic deformation of the loaded material to be evaluated. Analysis of the load test data indicates that simple relationships exist between deflection, settlement and elastic deformation for the subgrade so is under airport runways for deflections ranging from 0 to 0.7 inches. These relationships are noticeably different in sandy and in cohesive subgrade soils. Relationships between deflection, settlement and elastic deformation for flexible pavement surface load tests are very similar to those for the subgrade soils on which the pavement has been placed. In all cases, the ratio of elastic deformation to deflection decreases, as the deflection of the bearing plate under load is increased. Relationships between deflection, settlement, and elastic deformation appear to be relatively constant, regardless of the diameter of the bearing plate. For any given total deflection, the ratio of settlement to deflection increases with the number of repetitions of load required to attain that deflection.

14. A Study of the Interactions of Selected Combination of Subgrade and Base Course Subjected to Repetitive Loading Tests. John A. Havers. Purdue University Thesis for Ph.D., Lafayette, Ind., June 1956.

This thesis reports the results of a laboratory study initiated to investigate the effects of repetitive loading on selected combinations of subgrades and base courses. Two subgrades were studied. Two gradations of base course also were studied, both of which were well-graded mixtures of glacial gravel from Lafayette, Ind. with a maximum size of 3/4 inc. The first of these, designated as "open-graded," had no material passing the #80 U.S. sieve; the second, referred to as "dense-graded," had 7 percent by weight passing the #200 U. S. sieve.

A description of the compressed air actuated repetitive loading equipment is included. Two types of loading were utilized: "Single-acting", in which the loading returned to a zero position after each load application, hence had a length of stroke which increased as the deflection in the base course-subgrade system increased. To each specimen, 40,000 load repetitions were applied at intervals of 4 sec. Each load was sustained for 0.3 sec.

The laboratory study was designed to investigate at two levels the factors of subgrade type, base course type, subgrade compaction, base course compaction, and applied pressure.

The subgrade was compacted statically in 7-in. I.D. lucite cylinders to 95 percent of the unit weights obtained in the standard and modified AASHO compaction tests. A combination of vibration of vibration dynamic compaction was used to place base course samples on the compacted subgrade, at relative densities of 0.75 and 0.95. Both double-action and single-action tests were performed on combinations of subgrades and base courses at 10-psi and 40 psi applied pressure. Similiar tests also were performed directly on the subgrades and on the base courses.

Open-graded base courses were found generally superior to densegraded bases, since samples with the more permeable base course had a smaller total deflection and a lesser weight of pumped material. Similarly, combinations with the more plastic Frederick subgrades were found to perform slightly better than those with the less-plastic Crosby subgrades. Increasing the compaction of the subgrade was found decidedly beneficial for all samples, although an increase in the base course compaction appeared to have little effect. An increase in pressure accelerated the onset of pumping and increased its severity.

15. Highway and Public Works Engineers Aided by New Strain and Deflection Measuring Devices. AMINGO Laboratory, v 12 nol, p 7, Jan. 1955.

Two devices announced recently should be of great interest to highway and public works engineers. One is a soil strain meter for measuring strains within earth fills, embankments, and other earthworks. The other is a deflection gage for measuring movement of concrete pavements, dams, embankments, and the like.

Direct determinations obtained by means of these devices are particularly important as a check on the aid to the theory of design. Correlations with stress measurements are than possible in the determination of the modulus of elasticity at internal points of earth or concrete structures.

Either device may be permanently or temporarily embedded individually at various remote or inaccessible locations in dams, embankments, pavements, etc., either before or after construction. Readings may be taken intermittently or recorded continuously on automatic devices.

Deflection measurements are accurat to within 0.001 inch. The gage itself is capable of far greater accuracy but the mounting accuracy is usually of the order of 0.001 inch.

Electrical parts are sealed against effects of moisture, acids, and alkalis usually encountered in soil and concrete. Temperatures effects are negligible.

16. Dynamic Testing of Pavements, W. Heukelom, C. R. Foster, ASCE Proc v 86 (J Soil Mechanics & Foundations Div) n SML Feb. 1960 pt 1 paper 2368 p 1-28.

Each time vehicle passes over pavement, surface is deflected and rebounds, creating strain conditions for 0.01 to 0.1 sec; method used in Netherlands for simulating and studying such dynamic conditions in pavements, base courses and subgrades; use of single frequency monochromatic wave vibrator and of three point bending machine for determination of dynamic Emodulus and strength of asphalt structures.

17. Benkelman, A. C., "Analysis of Flexible Pavement Deflection and Behavior Data", Nat'l Research Council--Highway Research Board Bul 210, 1958, p 39-48.

In the WASHO Road Test there was a pronounced difference in the performance of the edge and center portions of the bituminous pavement, as well as a great difference in behavior of sections with 2 inch of surfacing and those with 4 in. of surfacing.

This paper presents a series of reactions to indicate to what extent the over-all pavement structure thickness and the seasons of the year enter into the differences in behavior of the edge and center portions of the pavement, and into the difference in behavior of the sections with 2-in. and 4-in surfacing.

18. Benkelman, A.C., R. I. Kingham and H. Y. Fang, "Special Deflection Studies on Flexible Pavement", Nat'l Research Council Highway Research Board Spec Rep 73, 1962, p 102-120.

The flexible pavement performance study at the AASHO Road Test indicated that the life of a pavement was related to the level of pavement deflection as measured with the Benkelman beam. It is probable, therefore, that planners of satellite or pavement evaluation programs will include measurements of pavement deflection in their experimental programs. In order to interpret the measurements of pavement deflection taken in any experimental program, some knowledge of the factors that affect the measurement is required.

At the AASHO Road Test special pavement deflection experiments were conducted to determine the effect of varying the

Benkelman Beam procedure and to consider an alternative method of measurement using an electronic device. Numerous other special experiments were carried out to determine the relationships of pavement deflection to wheel load, vehicle speed, tire pressure and pavement temperature. In addition, a program of plate load testing made possible a correlation between plate load test data and Benkelman Beam data.

Test data are summarized by means of tables, graphs and mathematical equations. The equations express the pavement deflections as functions of wheel load, vehicle speed and pavement temperature.

19. Bode, O. and others, "Comparison of different methods of determining the dynamic wheel load", Deutsche Kraft n 131, 1959, 33 pp. (German) M.I.R.A. Translation No. 1/63.

Because of the growing importance of the dynamic forces between wheel and road, several German engineering colleges have developed methods of measuring the dynamic wheel loads of motor vehicles. The methods compared in the first part of the present study are those of the Aachen, Brunswick, and Hanover colleges. Aachen determines the wheel loads by measuring the accelerations of axle and superstructure. The Brunswick method used the tire as a measuring spring. The variations in the distance between axle and road surface resulting from tire deflections are measured by a capacitative technique. With the help of the load/deflection urve of the tire, the wheel loads can be calculated. The Hanover method is based on the relationship between the dynamic wheel loads and the resulting elastic deformations of the axle housing. Details of the test equipment, calibration, and methods of evaluation used by the three institutes are given.

To compare the three methods, wheel-load measurements were made simultaneously on the same vehicle, a 10-ton truck, by the test teams of the three institutes, each using its own method of measurement and evaluation. The test runs were made on a good and a bad road and on a roadway. The results are given in tables and diagrams.

A Second series of tests was made as above, except that the data were all evaluated by the same statistical method, and additional measurements were made during travel over sewer covers and transit lines. Potential sources of error inherent in the test methods are discussed.

Part 2 of the study compares the wheel-load measuring techniques of the Darmstadt, Munich, and Brunswick institutes. Darmstadt measures the bending stressed at two points in the rim base of a special test wheel. As the correct load is indicated only twice per wheel revolution, viz., each time one of the strain gages is vertically above the tire-ground contact center, no continuous wheel-load trace is obtained, and the method is statistical in character. In the Munich method, the transverse bulging of the tire resulting from vertical tire deflection is used as a measure of the wheel load. The bulging is scanned by two mechanical feelers which are so connected that the effects of side forces are largely eliminated. The Brunswick method was as described above.

The results were again statistically evaluated. The inherent sources of error are mentioned, and the advantages and disadvantages of the methods are compared. In Part 3, three methods are compared, all of which use the tire as a measuring spring. These are the Brunswick and Munich methods mentioned above and another method developed at Brunswick which also measures tires bulging, but by means of electric scanners. These tests were evaluated by direct comparison of the traces.

20. Hveem, F.N., "Pavement Deflections and Fatigue Failures." <u>Nat'l Research Council-Highway Research Board Bul</u> 114, 1955 p 43-87.

This is a continuation of the paper entitled "The Factors Underlying the Rational Design of Pavement" appearing in the 1948 Proceedings of the Highway Research Board. The original work indicated the importance of fatigue failures caused by resilience in the supporting soils. This paper describes the initial work of measuring deflections over a wide variety of pavements. Examples are shown illustrating the load-deflection curves where pavements are showing signs of a failure and on other sections where conditions are good or excellent. In general, the deflections are directly proportional to load, although not in all cases. The deflections are measured under both single-axle and tandem-axle loads and the relationship between these two types of loading are established for several types of pavement.

Laboratory methods are discussed including the design of a resiliometer for measuring the resilient characteristics of soil samples and the design of a fatigue testing machine for measuring the realtive flexibility of pavements. The study indicates that a comprehensive design procedure must provide a pavement structure that will either be capable of surviving the fatigue resulting from continuous flexing or have sufficient "stiffness" to reduce the flexing to an acceptable value.

21. "Information Bulletin on Dynamic Testing of Roads and Runways, No. 1", Shell International Research Maatschappij N.V., Koninklijka/Shell-Laboratorium, Amsterdam, 1961, 13p.

This is the first of a series of bulletins whose pulications was decided upon at the Symposium on Vibration Testing of Roads and Runways held in 1959. It contains the following brief communications on new results obtained since the 1959 symposium: Dynamic test method according to Baum used in fatigue tests on bituminous road surfacings; Dynamic influences on measurements with soil pressure cells; The interpretation of surface wave propagation data and Investigation of roads with forced vibrations.

22. Heukelom, W., and C.R. Foster, "Dynamic Testing of Pavements", ASCE Proc 86: (J Soil Mechanics & Foundations Div) n SML Beb 1960, pt 1, paper 2368, p 1-28.

Each time vehicle passes over pavement, surface is deflected and rebounds, creating strain conditions for 0.01 to 0.1 sec; methods used in Netherlands for simulating and studying such dynamic conditions in pavements, base courses and subgrades; use of single frequency monochromatic wave vibrator and of three point bending machine for determination of dynamic Emodulus and strength of asphaltic mixtures.

23. Croney, D. and G. F. Salt, "Three Full-scale Road Experiments and Their Implication in Relation to Pavement Design ", Proc 5th Int Conf on Soil Mech and Found Eng., Paris II, pp 199-206, 1961.

The paper describes three experiments on the design of flexible road pavements carried out in Great Britain on heavily traveled roads since the last war. In each, sections of different thicknesses have been laid on subsections of known properties. Studies have been made of the relative contributions of various base and surfacing materials to the performance of the pavement.

The results show that sections surfaced with hot rolled asphalt have performed better than similar sections surfaced with bitumen macadam. Where a hot-rolled asphalt wearing course was used, sections thinner than the CBR design thickness performed satisfactorily for periods up to 9 years (the duration of the observations). When bitumen macadam surfacings were used, sections thicker than the CBR needed some maintenance of the surfacing to counteract the deformations that occured under traffic and to restore a satisfactory riding surface.

Sections with a bound base (tar-coated stone) deformed less than similar sections using crushed stone and gravel bases.

24. Hudson, W. R., "Comparison of strain measurements on AASHO Road Test and existing theories for rigid pavements", Paper presented at the 43rd annual meeting of the Highway Research Board, January 1963.

Existing rigid pavement design equations primarily spring from the theory of H. M. Westergaard in the 1925 Highway Research Board Proceedings. Some of these design equations are based on empirical modifications of the original theory, others are merely simplifications. These empirical modifications have been developed in several instances from strain measurements taken under static loads. Recent developments in the field if electronics made dynamic strain measurements much more accurate and feasible than they were formerly. Using such new equipment, approximately 100,000 individual strain gage readings were made under dynamic loads in conjunction with the AASHO Road Test.

This paper discussed these strain measurements and compares them with the static measurements used to develop existing empirical design equations. They are also compared with the original Westergaard theory. The results of such comparisons could form the basis for modifying empirical design equations to more nearly account for the dynamic load effect.

25. Boramisa, T. and L. Gashpar, "Determining the load capacity of road surfacings by the measurement of surface deformation under load", Avtom Dorogi (Moscow, USSR) 25: n 8, 1962 p. 28-30. (In Russian).

Experience gained in Hungary since 1955 in the use of an instrument similar to the Benkelman beam is reviewed. The application of the method which differs from that used in other countries is explained. An illustrated description is given of the design of the instrument; deflections in a pivoted beam 2.4 m long are recorded by a needle dial. Surface deformations under a 5-ton load were measured to within 0.01 mm by two beams each extending from between the double rear wheels of the test lorry. Measurements were made 1.2 m from the edge of flexible surfacing and in the center of concrete slabs at intervals of 200 m. Investigations have bean carried out on almost all the road network of Hungary.

The vehicle is left in position for not more than 1 min and then moved 3 m and another measurement is made; if the specified tolerance is exceeded a third reading is taken. At least 15 km of road can be tested per day. A table of limit deformation values for various surfacings is given. A 1-cm rolled asphalt course was found to be the equivalent of a 3.5-cm course of crushed stone aggregate.

26. Bonse, R. P. H. and S. H. Kuh, "Dynamic forces exerted by moving vehicle on a road surface", Nat'l Research Council--Highway Research Board Bul 233, 1959, p 8-32.

This paper describes an apparatus for measuring the forces exerted at a point on a road surface by the wheels of moving vehicles. Detailed results are presented of measurements of three force components; vertical force, and longitudinal and transverse horizontal force components. The investigation included a study of the influence on these forces of tire inflation pressure, speed, acceleration, wheel load, height of measuring study above road surface, etc.

Seven different vehicles were used covering a range of wheel (tire) load from 135 kg to 2,540 kg (300 lb to 5,600 lb), and a speed range of 15 kph to 75 kph (6 mph to 47 mph).

27. Schnitter, G. and F. Muller, "The deflection of road pavements, under a wheel load", Strasse u. Verkehr 48: n 2, 1962, p 51-64 (In German).

A method used by the Eidgenossische Technische Hoshschule, Zurick, for optical measurement of pavement deflection by means of a precision leveling instrument is described, and results of measurements are given. The following aspects of the method are discussed; (1) measurement on existing heavily-trafficked roads; (2) factors affecting test results; (3) evaluation of different types of road design; (4) observations and comparisons of airfield pavements constructed on a weak subgrade; (5) control of construction work; (6) evaluation of the stress on a pavement caused by specially heavy vehicles.

28. Williams, Stuart and Allan Lee, "Load-deflection study of selected high-type flexible pavement in Maryland" Nat'l Research Council--Highway Research Board Bull. 177, 1958, p. 1-20.

A cooperative program of load-deflection tests of several high-type flexible pavements in Maryland was inaugurated in the spring of 1955. A single test consisted of the application of a slowly moving 11,200-lb wheel load of a single-axle truck to an arbitrarily selected point on the pavement and the measurement of the resulting pavement deflection and rebound. Measurements were made at a point between the dual tires by means of the pavement deflection indicator known as the Benkelman Beam. Tests were made in the spring and in the fall at approximately 1,000 marked locations over a distance of about 85 lane miles. The pavements tested range in age from two to eleven years and are in excellent condition.

This report contains a description of the pavements studied, the test procedure used, and the results of the tests conducted to date.

29. Goodwin, W. A. Chairman, "Symposium on flexible pavement behavior as related to deflection", Proc Assn Asph Pav Techn 31: 1962, p 208-399.

Contains nine papers presented at the symposium. They are:

Method of measurement, F. N. Finn.
Significance of pavement deflections, C. L. Monismith.
Flexible pavement deflections--methods of analysis and interpretation, E. J. Yoder.
Observations of the significance of pavement deflections, J. H. Havens.
Deflection measurements in controlled test sections, R. G. Ahlvin.
Correlation of load deflection with design and performance R. E. Baker.
A comparison of flexible pavement performance with structure, J. R. Sissett and M. C. Ford.
Pavement deflection and rebound measurements and their application to pavement design and evaluation, G. Y. Sebastyan.
Pavement deflection as related to the ultimate capacity of flexible pavements, W. S. Housel.

30. "A guide to the structural design of bituminous-surfaced roads in tropical and sub-tropical countries", Gt. Britain, Dept. of Scientific and Industrial Research Road Research Laboratory, Road Note 31, March 1962, 16 pp.

This note is intended to provide a guide to the engineer in designing bituminous-surfaced roads in the tropics.

In most of the developing countries in the tropics, road traffic is increasing rapidly, in both weight and numbers. Annual increases in traffic flow of the order of 15-20 percent are not uncommon. In some countries the load-carrying capacity of roads and bridges mades it necessary to put special restrictions on vehicle weights; on the other hand there are mounting pressures to extend the mileage of bitumnous-surfaced roads capable of carrying vehicles with axle loadings up the limits accepted in more developed countries.

One of the main tasks of the Road Research Laboratory in their work on road building in the tropics has been to derive methods of design for bituminous-surfaced road pavements. The method of design proposed in this Note makes use of the CBR test as a measure of the strength of the soil. An injuiry has shown that the CBR test is by far the most widely used in pavement design in tropical countries, and there is much to be said for using testing techniques which are already familiar and for which there is a considerable background of experience.

Moisture conditions have an important influence on the strength of a soil and a wide range of moisture conditions is encountered in different climates found in the tropics. The results of studies by the Laboratory to determine the influence of climate on moisture conditions in soil under roads and runways have provided the basis for the simple classification of tropical climatic enviroments into three categories which is used in this Note.

Road pavements are normally designed and constructed so that they will be adequate to carry the traffic expected over many years. In Great Britain, for instance, a 20-year life is usually assumed, and the roads are designed to carry the increasing traffic expected during that period, less developed countries where traffic is increasing rapidly may well expect it to increase 15 times or so over a 20-year period. Often they cannot afford to build roads to meet the traffic intensities predicted 20 years hence; nor is it economically desirable that they should. It will generally be more appropriate to design roads to meet the requirements of traffic for a shorter period, perhaps 10 years, and to use a form of construction that can be readily strengthened as traffic increases. This pattern of stage construction to meet the requirements of rapidly increasing traffic over a wide network of roads forms the basis for the recommendations of this note.

31. "Remotely-controlled measuring devices", Concrete and Constructional Engineering 54: n 11, pp 390-391, November 1959.

An electronic device is now available for measuring strains, deflections, pressures, forces, and temperatures, and it is stated that the measurements are accurate within 1 percent. The apparatus comprises a transmitter and a receiver. The transmitter contains a wire that can be made to oscillate by excitation from the receiver. The damped natural vibration of the wire varies with the quantity to be measured, and is transmitted to the receiver that contains a wire whose frequency may be tuned to that of the transmitter. The vibrations of the wire in the receiver is adjusted until a circular or elliptical figure is obtained on the screen, indicating that the vibrations are synchronized. The adjustment necessary of the transmitter multiplied by a constant is the required measurements.

The transmitter made from a variety of types of measurements. These apparatus are made in Hamburg.

32. Flexible pavement design research, Nat'l Research Council, Highway Research Board - Bul n 233 1959, 56 p.

Papers presented at 38th Annual Meeting Jan. 5-9, 1959, in Washington DC: Development and Performance of Flexible Pavement on New Jersey Turnpike, H. W. Goldberg, 1-8; Dynamic Forces Exerted by Moving Vehicles on Road Surface, R.P.H. Bonse, S. H. Kuehn, 9-32; Reevaluation of Kentucky Flexible Pavement Design Criterion, W. B. Drake, J. H. Havens, 33-56.

33. Traffic Bearing Structures-Pavings, Brit. Standards, Instn. Brit. Standard Code of Practice CP 2006, 1960, 204 p.

Code deals with designs, construction and maintenance of pavings and for use of road vehicles, pedestrains, and aircraft; specific references to airfield practice is made where this differs in detail from that for roads; code is in five parts covering; design and construction of foundations; concrete roads and airfields; surfacings other than concrete footways, cycle tracks and verges: surface water drainage.

34. Correlation of Vehicle Design and Highway Design, R. A. Haber, D. K. Witheford, ASDE-Proc v 86 (J Highway Div) n HW 2 June 1960 pt 1 Paper n 2529 p 15-35.

Trends in vehicle design; aspects of diversity, weight, and speed, resulting requirements concerning highway pavement structures, lane width, alignment, and clearances, etc; insufficient coordiantion of vehicle design and highway design is placing highway program in precarious position; situation calls for unified research approach supported by industry and all interested groups and agencies.

35. Earth motion beneath prescribed boundary displacement, R. C. Geldmacher, J. W. Dunkin, R. L. Anderson ASME - Trans - J. Applied Mechanics v 27 Ser E n 1 Mar 1960 p 120-4.

Problem was stated in terms of 2-dimensional model and attempt was made to design corresponding experiment; relative deflections between surface of earth and points of increasing depths, within earth were measured max depth being 42 ft 7 in. theoretical and experimental results are compared; beneath rigid pavements. Paper 59-A-3.

36. Loading design for asphalt pavements, J. C. Johnson. Pub Works v 90 n 1 Jan. 1959 p 77-80, 162-164, 176-7.

Economy requires use of locally available materials for lower courses or layers and suitable design for anticipated conditions; consideration of density of vehicles and maximum single axle load; alternate designs should be made to enable consideration of various combinations of available materials; cost analysis of alternate designs; type and CBR value of subgrade soil determines required thickness of structure; use of two subbases, lower being "improved subgrade".

37. Stresses and displacements in layered systems, M. R. Mehta, A. S. Veletsos, Univ. of Ill. Civ Eng. Studies - Structural Research Series n 178, June 1959, 109 p.

Analysis of semi-infinite layered elastic medium subjected to axially static forces at surface; effect of body forces is not considered; system may have arbitrary number of horizontal layers; pertinence to solution of problem is based on theory of elasticity; airport and highway pavements and certain problems in foundation engineering. 20 refs.

38. Study of relationship of pavement cost to vehicle weight, R. F. Baker, E. H. Karrer, Ohio State University Eng. Experiment Station - Bul n 161, July 1956, 76 p.

Report is concerned with amount of highway costs for which various groups of highway users are responsible; factors in pavement design, soil conditions, availability of materials, etc; study was restricted to cost for 2-lane pavements on new construction of main highways; vehicle characteristics and physical or natural obstacles are major factors affecting such costs. 26 refs.

39. Computation of Load stresses in three-layer elastic system, W.E.A. Acum and L. Fox. Geotechnique v 2 n 4 Dec 1951 p 293-300.

Burnister's method applied to 3-layer road system and results given for wide range of parameters involved; variables are radius of loaded area, thicknesses of two top layers, and elasticities of three layers; formulas for horizontal and vertical stress components; no use made of relaxation method of Southwell: tables.

40. Loads transmission test for flexible paving and base courses - I. R. C. Herner and W. M. Aldous, U. S. Civ Aeronautics Administration, Tech Development Report n 108 Apr 1950 (received 1952) 10 p. ills.

Present status of flexible paving design; special testing rig for some of basic information necessary for more accurate and rational approach to problem; operating methods and anticipated used to test data.

41. Pavement load deflections measured by spring-supported subgrade, R. C. Herner. Eng. News Rec. v 148 n 11 March 13, 1952 p 58.

Method of measurement of pavements deflections; tests apparatus used by Civil Aeronautics Administration; most of tests were made in 8 in. of gravel; illustrations.

42. Method of determination of critical displacement in plate bearing tests, B. Fasu. Instn. Engrs. (India) - J v 32 n 2 Dec. 1951 - p 23-51.

Relation between settlement under load and bearing capacity of soil supporting that load; equations of bearing capacity and settlement; apparatus and experimental procedure; results; relation between property of soil and depth.

43. Investigation of field and laboratory methods for evaluating subgrade support in design of highway flexible pavements, R. F. Baker and W. B. Drake, Univ. of Kentucky, Eng. Exp. Station Bul 13, Sept. 1949 119 p.

Method of design of flexible pavements by means of relationships between field supporting values and laboratory test results; flexible pavement design as affected by load, thickness, and subgrade support; traffic evaluation and determination of traffic classification.

44. Pavement design for roads and airfields, E. H. David. Great Britain Dept. Sci. & Indus Research - Road Research Laboratory Tech paper n 20 1951 50 p; see also abstract in Pub. Works v 82 n 11 Nov. 1951 p 40-2, 69.

Typical forms of bituminous road construction; correlation between Casagrande's airfield soil calssification, Public Roads Administraction classification, California bearing ratio and Westergaard's Modulus of subgrade reaction; theoretical methods based on Boussines theory, shear strength method, analysis by Westergaard and Burmister. Biblio.

45. Van Der Poel, C., Vibration Research on road construction. Sump. Dynamic Testing Soils, ASTM, Special Tech. publication no. 156, pp. 174-185, 1954.

The possibilities and merits are discussed of a method for measuring the stiffness of a road construction under a vibratory loading. This method forms the dynamic counterpart of the well-known static plate bearing tests. The measurements are reproducible, however, than methods such as wave velocity measurements and measurements under actual traffic conditions, vibratory loading has the advantage of giving clear and straight forward results that allow a simple interpretation. The method can be easily standardized and it can be handled by any skilled engineer. The results have so far been in agreement with road behavior and practical engineering experience.

46. Baum, G., "Dynamische Untersughungen an Strassen", Strasse u Autobahn 10: n 8 Aug 1959, p 277-82.

Dynamic testing or roads; measurements made at about 250 testing points on German roads; use of vibration is between 10 to 75 cps; amplitude of response, characteristic for various constructions; and conditions of road is shown by geophone stresses measured by millivoltmeter; examples of measurements are given.

47. Harris, H., "Electronics assists in highway construction", Electronics 32: n 51, Dec 18 1959, p 69-71.

Electronic instrumentation for testing highway construction described; instruments measure various effects of highway traffic on test pavement and moisture content and sub-surface temperature at test site; instruments speed acquisition of test data, permit rapid engineering and statistical analysis.

48. Heukelom, W., "Analysis of dynamic deflections of soils and pavements", <u>Geotechnique</u> 11: n 3, pp 224-243, September 1961.

The deflections of soils and roads under sustained vibration conditions have been observed. The resistance to deformation is expressed in the dynamic stiffness.

The dynamic stiffness is found to consist of an elastic part, which is considered independent of the frequency, and a part which depends on frequency. The latter is split into a damping and a mass effect.

The magnitude of the elastic stiffness, the damping and the mass is discussed, and special attention is paid to the linearity of the system and to the fact that the mass effect decreased at relatively high frequencies.

Under the shock type of loading by traffic, mass effects are found to be less important than under the conditions of sustained vibrations. It is derived that the traffic stiffness is almost equal to the elastic part of the dynamic stiffness, which can be measured fairly accurately by means of vibration machine.

49. "Investigation of pressures and deflections for flexible pavements; development of representative soil strengths from laboratory tests," U. S. Army Engineer Waterways Experiment Station, Corps of Engineers Tech Memo No. 3-323, Report 5, December 1960, 43 pp.

One of the most important features of the comprehensive study of the distribution of stress, deflection, and strain in soil masses, of which the triaxial tests are a part, is the determination by measurement of the stress-strain relations existing within large soil masses subjected to surface loading. In two earlier curves were developed, for a vertical orientation, that are representative of the actual stress-strain relations existing within a large homogenous clayey silt and a large homogenous sand test section during application of surface loads. The triaxial test program had as it 's objective the establishment of a test method or procedure whereby stress-strain curves developed from laboratory tests on small, laboratory samples would duplicate the field data curves.

By trial and error it was found that curves developed in variable-confining-pressure triaxial tests on undisturbed samples from the homogenous clayey silt test section yielded stress-strain curves duplicating the field data so closely as to be identical for practical purposes. Similar results were obtained from prepared samples of sand from the homogeneous sand test section.

It is believed that a theoretical loading curve can be used with the variable-confining-pressure triaxial test to develop stress-strain relations for soils of the type used in the tests reported, and perhaps for other types as well. It is recommended that in future work the test methods developed in the triaxial study be used to determine moduli of deformation, and that the probably validity of these moduli be considered in order that the test methods developed in the study may be further substantiated.

50. Jones, R. and A. C. Whiffin, "A survey of dynamic methods of testing roads and runways", Nat'l Research Council--Highway Research Board Bulletin 277, 1960, p 1-7.

The object of this paper is to indicate how far dynamic methods of testing roads have developed in the various countries and to summarize the present state of the work.

The vibrational method of testing roads originated in Germany where, before World War II, mechanical vibrators were used to investigate the mechanical properties of different types of soil. During and after World War II, further developments of the technique were made by the Royal Dutch Shell Co.'s laboratory at Amsterdam, and the method was applied to testing roads and runways. The dynamic stiffness of the construction was deduced from the applied vibratory force and the resultant amplitude of vibration. Tests on a variety of roads indicated that high values of the stiffness were associated with strong forms of construction, and low values with weak ones. The ultimate objectives of this form of nondestructive test are to predict the performance of roads under traffic and to determine where and when failure of the construction is beginning. Testing techniques to these ends have been developed recently in Germany.

The British Road Research Laboratory has been studying the velocity of propagation of vibrations in layered constructions using electro-mechanical vibrators covering a much wider frequency range than is possible with the rotary machines normally employed. The relations obtained between velocity and frequency are being studied to deduce the elasticities and thickness of the layers partly to assess the quality of the construction and partly to obtain data which might be later employed for pavement design is still in its infancy and it is too early yet to decide whether or not such a design technique will ultimately be possible.

51. Jones, R., "Following changes in the properties of road bases and subbases by the surface wave propagation method", Civ Eng & Pub Works Rev (London) 58: n 682, p 613-617, May 1963, n 683, p 777-780, June 1963.

The surface wave propagation method has been developed at the Road Research Laboratory for obtaining the elasticity properties and, where possible, the thicknesses of the constituent layers of a road. By this method, measurements are made at the surface of the road at frequences in the range of 30 to 30,000 cycles per second and the relation between velocity and wavelength is analyzed theoretically to yield the required information. Repetitive tests on experimental roads over a period of about five years have emphasized the particular usefullness of the method as nondestructive method of following the changes in the properties of the base materials caused by time and traffic.

Examples are given which show that: (1) under favorable conditions, considerable increases (threefold or more) can be obtained in the elastic modulus of a sand subbase or a wet-mix slag base material because of compaction by traffic. These increases lead to improvements in the load-spreading properties of these materials. (2) Cement-bound bases usually have extremely high elastic moduli in their uncracked condition. The development of cracks in these bases can be detected by the surface wave propagation method and it has bean found that weak or thin cement-bound bases become extensively cracked their effective elastic moduli beome comparable with those of a well-compacted crushed-stone or wet-mix base. (3) The surface wave propagation method has detected stripping in bituminous materials which also leads to a decrease in the effective elastic modulus and load-spreading properties of the base.

52. Jones, R., "Measurement and interpretation of surface vibrations on soil and roads", Nat'l Research Council--Highway Research Board Bulletin 277, 1960, p 8-29.

The Road Research Laboratory is developing nondestructive techniques for measuring the dynamic mechanical characteristics and thicknesses of the layers forming a road. The mathematical theory for computing stresses and deformations requires knowledge of these data and the development of these testing techniques is a necessary step torwards a system of pavement design based on the stresses encountered in the road and the mechanical properties of the materials.

Apart from this, the techniques are already able to provide information of immediate value in that they provide data of assistance in appraising the performance of experimental and other roads under traffic, they can be used to locate areas where variations of mechanical properties or thickness occur, and they can be used to study the changes produced by traffic and weather.

The first part of this paper deals with the experimental technique for measuring the wave length and phase velocity of mechanical vibrations propagated along the surface of soil or road constructions. The vibrations are produced electromechanically by apparatus working within the frequency range from 40 to 60,000 c/s and have wave lengths ranging from a few inches to several feet. The results are normally expressed graphically as the relation between phase velocity and the wave length obtained at selected frequencies. This curve has a number of characteristics which depend on the elastic properties and the thicknesses of different parts of the construction; the second part of the paper discussed theoretical analyses to calculate these parameters. So far, most of the work has been limited to experimental constructions and all the relevant data concerning thicknesses and type of material have been known, while vibratory experiments have also been made, where necessary, on laboratory specimens of the materials to determine their elastic properties. These data have enabled checks to be made of the validity of predictions from the vibrational experiments.

53. Jones, R., "Surface wave technique for measuring the elastic properties and thickness of roads: theoretical development". Brit J Appl Phys 13: n 1, 1962, p 21-9.

The theoretical development of the experimental technique for measuring the elastic properties of the layers which make up a road is described. A knowledge of these properties is required in the development of a fundamental method of pavement design. The elastic properties are deduced from measurements of the wavelength and velocity of vibrations of known frequency along the surface of the road, and this paper develops the theory of the method of analysis of the relation between velocity and wave-length for pavements with one and two superficial layers. The paper was prepared at the Road Research Laboratory, Harmondsworth.

54. Knight, William R. and Jong Ping Chen, "Two-sample method for pavement deflection survey", ASCE Proc 88: J of the Highway Div No. HW2, Sept 1962, p 37-45, n 3280.

A method of taking deflection measurements on pavements in two stages described. First stage determines number of observations required in second stage.

55. Ormerod, A., "The deflexion of an elastic structure", Structural Engineer (GB) 40: n 6, June 1962

Basic concepts; relationship between cross-flexibilities; derivation of general relationship; use of relationships; note on form of relationship; applied moments response; derivation of general relationship.

56. Preus, C. K. and L. A. Tomes, "Frost action and load-carrying capacity evaluation by deflection profiles", Nat'l Research Council--Highway Research Board Bul 218, 1959, p 1-10.

This report describes the experimental use of a Benkelman beam with a Helmer recorder attached as a means of measuring the changes in load-carrying capacity of flexible pavements that occur as a result of a frost action. An attempt also has been made to correlate the values of load-carrying capacity as determined by the use of the well estabilished plate bearing test with similar load-carrying capacities as determined by use of the Benkelman beam with the Helmer recorder attached.

About 1956 a Benkelman beam was made available to the Highway Research Board's Committee on Soils Calcium Chloride Roads. With this apparatus considerable data were collected in Alabama, Virginia, and particularly in Minnesota, on maximum deflections and residual deflections of flexible pavements under comparatively realistic loading.

57. Trollope, D. H., I. K. Lee and J. Morris, "Stresses and deformations in two layer pavement structures under slow repeated loading," Proc Australian Road Research Board Paper No. 38 1: pt 2, pp 693-721, 1961.

Successful performance of a pavement structure depends on elastic behavior of the constituent materials under repeated loading.

A laboratory examination of the behavior of sand and a sand-bitumen mix suggests that these granular materials can be conditioned to behave quasi-elastically provided they are proof-loaded to stress level higher than that required in service. The stress strain characteristics of these materials under slow repeated loading are such that the "true" elastic modulus is that measured on the unloading cycle in a compression test (the rebound modulus) not, as has been assumed previously, the value obtained from a single loading cycle.

Tests on model pavements in the laboratory have indicated that the stresses in two layered systems follow the predictions of the linear elastic theory colsely with respect to mode of distribution but the evaluation of the effective modulus still presents a serious problem. It is likely that the behavior is non-linearly elastic. It can also be shown therefore that, in the absence of proof-loading, elastic theory cannot predict adequately the total deformation of a pavement surface.

58. J. R. Morgan and A. J. Scals. Australian Road Research (Australian Road Research Board, 60 Denmark St., Kew e. 4, Victoria Australia), Vol. 2, No. 5, pp. 12-26, Sept. 1965.

A common method for evaluating the structural adequacy of in-service roads is in terms of the deflection under a loading test. A number of different types of pavement were tested by the dual wheels of a slowly moving vehicle with three applied axle loads. The effects of those loads on the vertical deflections both in the longitudinal and transverse direction are presented. Measurements were made at the surface of the pavement and the subgrade level. The influence of some tractive stresses on these deflections is also included.

59. Certain Aspects of the Design of Flexible Pavements, N. Ivanov, A. Krivisaki, I. Tcherkassov, V. Babkov and A. Biroulia.(USSR) Proc. 5th Int. Conf. on Soil Mech. & Found. Eng., Paris, Vol. II, pp. 245-250, 1961. (Available from Stechert-Hafner, Inc. 31 E. 10th St., New York, N. Y.

The authors propose an improved method of designing flexible road pavements, based on the theory of elasticity applied to multilayer systems and on parameters determined from loading tests of impact type. The authors suggest two methods for determining the thickness of a road pavement: (a) using permissible vertical deflections on the pavement of from 0.0025 to 0.005 under repeating application of impact loads which do not cause fatigue; (b) using local shear stress in the underlying soil or in one of the layers of the pavement.

Item (a) involves a determination of the moduli of elasticity under the application of heavy wheel loads for definite period. Item (b) of the angle of internal friction and the coefficient of cohesion of the soil. These two procedures are being developed and compared with information gained both in the field and the laboratory.

Experiments have proved that the parameters differ even where soil conditions and deflections are similar; special coefficients are used in order to allow for these variations.

A new method for determining rolling resistance has been developed.

The authors have devised a new apparatus for testing the traffic resistance of a soil surface. This device combines a conical densimeter with an equipment similar to that used for vane tests.

60. Highway Research Record, F. H. Scrivner, Research Engineer, Texas Transportation Institute, Texas A & M University. A New Research Tool for Measuring Pavement Deflection pp. 1-11. N_o. 129.

In connection with current research being conducted for the Texas Highway Department and the U. S. Bureau of Public Roads, it became necessary in 1964 for the Texas Transportation Institute to measure deflections on several hundred flexible pavement sections on highways throughout Texas. Before initiating a program of that size, we decided to investigate a device recently developed by Lane-Wells Division of Dresser Industries, Inc., capable of recording the deflection of a road surface caused by the application of a relatively light oscillating load. If it could be shown that the deflection so induced correlated reasonably well with static deflection measured by conventional means, we flet that certain unique advantages of the device would warrant its use in our research.

This report describes the Lane-Wells measurement system, gives the results of the preliminary investigation, and presents data illustrating how the deflection basin is affected by variations in the structural design of the pavement. It also describes an experience in this research.

61. Highway Research Record, No. 129, N. A. Huculak, District Engineer, Department of Public Works of Canada, Calgart, Alberta. pp. 12-27.

Contrary to normal practice employed in the design and construction of a modern highway, the maintenance aspects of providing this facility are seldom based on adequate pre-engineering and evaluation data. Sufficient time is seldom available to perform a thorough diagnosis of the maintenance problem through conventional sampling and testing techniques. A method of pavement evaluation based on surface deflections and observed performance of existing routes is described and summarized in the form of charts which permit a ready appraisal of the problem as an aid in the establishment of maintenance warrants and highway planning.

62. Highway Research Record, No 129, F. Bolivar Lobo Carneiro, Materials Engineer, Guanabara Highway Department and Consultant Engineer, Proenge Ltd., pp. 28-59.

One of the most difficult tasks of the maintenance engineer is to anticipate pavement maintenance requirements; it is also necessary for him to have an accurate knowledge of the structural performance of each section of the pavement.

The aim of this paper is to demonstrate how deflections when measured by a Benkelman beam can assist the maintenance engineer in evaluating the structural condition of pavements in terms of required maintenance.

This paper describes methods of measuring deflection using the Benkelman beam, analyzes the disadvantages of the methods used on the WASHO Road Test, and presents the methods used by the Canadian Good Roads Association, which we propose be standarized and adopted in Brazil.

The author also discusses modern methods currently used to design and plan pavement overlays, and describes the types of data which must be obtained in Brazil.

63. Highway Research Record, No. 129, Ernest Zube, Assistant Materials and Research Engineer, Materials and Research Department California Division of Highways. pp. 60-75.

This paper discusses the results of the use of the deflection method by the California Division of Highways for the evaluation of existing flexible pavements and the recommendation of suitable reconstruction. Since 1960, some 80 projects including state highways, county roads, and city streets, have been subject to deflection investigations by the Materials and Research Department of the California Division of Highways. The primary purpose of these investigations was the recommendation of appropriate corrective treatment. As a result of this intensive program, a large volume of data on the deflection attenualtion properties of various roadway materials has been accumulated and is presented in this report, along with the results of individual deflection data, and design criteria, which have evolved are examined in detail. In addition, economical and practical factors involved in making a specific recommendation are discussed. A separate section including work now bding done on the establishment of maximum deflection criteria which may be adjusted for variations in traffic volume. A brief analysis of radius of curvature data obtained with the Dehlen curvature meter is also included.